

Deterministic generation of polarization-entangled photon pairs in a cavity-QED system

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We propose a cavity-QED scheme that can deterministically generate Einstein-Podolsky-Rosen polarization-entangled photon pairs. A four-level tripod atom successively couples to two high-Q optical cavities possessing polarization degeneracy, assisted by a classical π -polarized pump field. The stimulated Raman adiabatic passage process in the atom-cavity system is used to produce the polarization-entangled photon pairs. The proposal is particularly robust against atomic spontaneous decay, which should have potential applications in quantum information processing.

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1. Introduction

Quantum entanglement is one of the most valuable resources in quantum information science, which has many applications in the fields of quantum computation and quantum communication, e.g., quantum cryptography, quantum teleportation and quantum network[1]. Recently great efforts have been made to controllably generate and detect entangled states, including the Einstein-Podolsky-Rosen (EPR) state of two qubits[2], Greenberger-Horne-Zeilinger (GHZ) state and W state of three qubits[3, 4], as well as other multipartite entangled states[5, 6, 7]. Since photons are the ideal carriers of quantum information, a large number of theoretical and experimental schemes have been proposed for producing entangled photons. The traditional optical parametric down conversion method is used to produce the entangled photon pairs[8], yet the process is stochastic in nature. In order to controllably generate the entangled photons, the cavity-QED scheme utilizing the coherent interaction of atoms and field modes of a cavity is proposed[9]. Cavity QED offers an almost ideal system for the generation of entangled states and the implementation of quantum information processing. Experimental and theoretical progress on the entanglement in cavity-QED with the strong-coupling limit[10] has been made, such as entangled atoms[11, 12], atom-photon entanglement[13] and entangled photons[14, 15, 16, 17, 18, 19, 20]. In this work, we have proposed a new cavity-QED scheme composing of a four-level tripod atom and two cavities to produce EPR entangled photon pairs. This scheme only needs one classical pump field, therefore it may be much easier to be implemented in experiments.

To implement the cavity-QED schemes for generating entangled photons, one has to consider the effect of atomic spontaneous decay on the coherent evolution of the system. This decoherence process may be harmful to preserving entangled state. The stimulated Raman adiabatic passage (STIRAP) can be used to overcome this problem. STIRAP was first used to coherently control dynamical processes in atoms and molecules[21]. It uses partially overlapping pulses to produce complete population transfer between two quantum ground states of an atom or molecule. In STIRAP the population adiabatically follows the evolution of the dark state[22, 23] and the excited state is never involved. Therefore, this is particularly robust against atomic spontaneous decay. The STIRAP technique is now widely used in the chemical-reaction dynamics, laser-induced cooling, atom optics[21] and cavity-QED systems[24, 25]. In this paper, we make use of the STIRAP technique in a cavity-QED system composing of two cavities to produce entangled photon pairs.

In the following, we present a cavity QED scheme which can deterministically produce EPR polarization-entangled photon pairs. A four-level tripod atom successively couples to two single longitudinal mode high-Q optical cavities possessing polarization degeneracy, assisted by a classical π -polarized pump field. The spatial profiles of the two cavity modes and the pump field have to be overlapped, which can provide a counterintuitive pulse sequence and maintain the two-stage STIRAP process[21]. Stage 1 is to produce a σ^+ or σ^- polarized photon in cavity 1 entangled with the atom by the first STIRAP. Stage 2 is to make the atom swap its entanglement with the photon in cavity 1 to the photon in cavity 2 by a second STIRAP. At this stage a two-photon polarization-entangled state is prepared and the atom returns to its ground state. The stimulated Raman adiabatic passage process is utilized in the cavity-QED system, which is robust against atomic spontaneous decay. This proposal should have potential applications in quantum information processing.

2. Generating entangled photon pairs by STIRAP

The system under investigation is shown in Fig. 1. It is composed of a four-level tripod atom and two identical high-Q cavities possessing polarization degeneracy. The ground state of the atom is labeled as $|g\rangle$, the two metastable states as $|a\rangle, |b\rangle$, and the excited state as $|e\rangle$. The transitions $|a\rangle \rightarrow |e\rangle$, and $|b\rangle \rightarrow |e\rangle$ are coupled by the cavity polarization degeneracy modes with the coupling coefficient $g_i (i = 1, 2)$, where i denotes the i th cavity. The transition $|g\rangle \rightarrow |e\rangle$ is driven by a classical π -polarized pump field with Rabi frequency Ω . The detunings for these transitions are $\Delta_1 = \omega_e - \omega_a - \omega_c$, $\Delta_2 = \omega_e - \omega_b - \omega_c$, and $\Delta_3 = \omega_e - \omega_g - \omega_p$, where ω_c and ω_p denote the cavity mode and the pump field frequency respectively, and $\omega_\alpha (\alpha = a, b, e)$ denotes the atomic level energy. The pump field and the cavity modes have to be overlapped spatially. We assume that all of them have the Gaussian modes, i.e., $\Omega(t) = \Omega_0 \exp[-(\frac{t-\delta t}{\Delta\tau_p})^2]$, $g_1(t) = g_{10} \exp[-(\frac{t}{\Delta\tau_c})^2]$, and $g_2(t) = g_{20} \exp[-(\frac{t-2\delta t}{\Delta\tau_c})^2]$. Here, $\Delta\tau_p$, and $\Delta\tau_c$ are the widths of the pump field and the cavity mode, and δt is the pulse center. We focus on the situation where the two-photon resonance happens, i.e., $\Delta_1 = \Delta_2 = \Delta_3 = \Delta$. This dark-state condition can make sure that the STIRAP in the cavity-QED system takes place. Under the dipole and rotating wave approximations[26], the interaction Hamiltonian for this atom-cavity system is (let $\hbar = 1$)

$$H_I = \Delta\sigma_{ee} + \Omega(t)\sigma_{eg} + \sum_{i=1}^2 (g_i(t)a_{i+}^\dagger\sigma_{ae} + g_i(t)a_{i-}^\dagger\sigma_{be}) + H.c., \quad (1)$$

where $\sigma_{\alpha\beta} = |\alpha\rangle\langle\beta|$, and $a_{i\pm}^\dagger$ is the σ^\pm circularly polarized photon creation operator in the corresponding mode. In the next two paragraphs, we give the details of generating polarization-entangled photon pairs by STIRAP.

Stage 1: Producing a photon in cavity 1 entangled with the atom. Suppose that the atom is initially prepared in the ground state $|g\rangle$, cavity 1 in the vacuum state $|00\rangle_1$, and cavity 2 in $|11\rangle_2 = a_{2+}^\dagger a_{2-}^\dagger |00\rangle_2$ [24, 25]. There are two pathways that the atom transfers from the ground state to the metastable states. After undergoing the STIRAP, the atom is prepared in state $|a\rangle$ or $|b\rangle$ with the same probability, and emits a σ^+ or σ^- polarized photon. The interaction Hamiltonian of the cavity-atom system at the present is

$$H_{I1} = \Omega(t)\sigma_{eg} + g_1(t)a_{1+}^\dagger\sigma_{ae} + g_1(t)a_{1-}^\dagger\sigma_{be} + H.c. \quad (2)$$

The system has the following dark state [22, 23]

$$|D_1\rangle = \{\sin\theta[\frac{1}{\sqrt{2}}(|a\rangle|10\rangle_1 + |b\rangle|01\rangle_1)] - \cos\theta|g\rangle|00\rangle_1\} \otimes |11\rangle_2, \quad (3)$$

where $\tan\theta = \frac{\Omega(t)}{g_1(t)}$, $\tilde{g}_1(t) = \sqrt{2}g_1(t)$, $|10\rangle_1 = a_{1+}^\dagger|00\rangle_1$, and $|01\rangle_1 = a_{1-}^\dagger|00\rangle_1$. We then consider the details of STIRAP process. The pulse sequence is counterintuitive in the sense that the two initially empty levels are coupled first, and then the initially populated level is driven by the pump field. Moreover, the two field modes must overlap partially. If the couplings $\Omega(t)$ and $g_1(t)$ change slowly enough, and $\lim_{t\rightarrow\infty} \frac{g_1(t)}{\Omega(t)} = 0$, the system will start in the state $|g\rangle \otimes |00\rangle_1 \otimes |11\rangle_2$ and end up in the state $\frac{1}{\sqrt{2}}(|a\rangle|10\rangle_1 + |b\rangle|01\rangle_1) \otimes |11\rangle_2$, following the adiabatic eigenstate given by Eq. (3). That is, when $\theta : 0 \rightarrow \frac{\pi}{2}$,

$$|D_1\rangle : |g\rangle \otimes |00\rangle_1 \otimes |11\rangle_2 \rightarrow \frac{1}{\sqrt{2}}(|a\rangle|10\rangle_1 + |b\rangle|01\rangle_1) \otimes |11\rangle_2.$$

As a result, the atom emits a polarized photon and is entangled with the photon.

Stage 2: The atom swapping its entanglement with the photon in cavity 1 to the photon in cavity 2. The atom enters cavity 2 prepared in a two-mode Fock state with just one photon in each mode [25]. It then interacts with the photons in cavity 2. After undergoing the second STIRAP process, the atom absorbs one of the photons. Now the atom swaps its entanglement with the photon in cavity 1 to the photon left in cavity 2 and returns to the ground state. At this stage a two-photon EPR polarization-entangled state is prepared. The corresponding Hamiltonian described the coherent interaction is

$$H_{I2} = \Omega(t)\sigma_{eg} + g_2(t)a_{2+}^\dagger\sigma_{ae} + g_2(t)a_{2-}^\dagger\sigma_{be} + H.c. \quad (4)$$

In this case, the dark state is

$$\begin{aligned} |D_2\rangle = & \sin\beta[\frac{1}{\sqrt{2}}(|a\rangle|10\rangle_1 + |b\rangle|01\rangle_1) \otimes |11\rangle_2] \\ & - \cos\beta[\frac{1}{\sqrt{2}}|g\rangle(|10\rangle_1|01\rangle_2 + |01\rangle_1|10\rangle_2)] \end{aligned} \quad (5)$$

where $\tan\beta = \frac{\Omega(t)}{g_2(t)}$. If the couplings $\Omega(t)$ and $g_2(t)$ change slowly, and let $\lim_{t \rightarrow \infty} \frac{\Omega(t)}{g_2(t)} = 0$, the system will begin at the state $\frac{1}{\sqrt{2}}|g\rangle \otimes (|a\rangle|10\rangle_1 + |b\rangle|01\rangle_1) \otimes |11\rangle_2$ and reach the state $\frac{1}{\sqrt{2}}|g\rangle \otimes (|10\rangle_1|01\rangle_2 + |01\rangle_1|10\rangle_2)$, following the adiabatic eigenstate by Eq. (5). That is, when $\beta : \frac{\pi}{2} \rightarrow 0$,

$$|D_2\rangle : \frac{1}{\sqrt{2}}(|a\rangle|10\rangle_1 + |b\rangle|01\rangle_1) \otimes |11\rangle_2 \rightarrow \frac{1}{\sqrt{2}}|g\rangle \otimes (|10\rangle_1|01\rangle_2 + |01\rangle_1|10\rangle_2).$$

Finally, the atom returns to its ground state $|g\rangle$, and the two cavity photons of different polarization have been entangled with each other. This is the central result of this work.

In order to verify the above STIRAP processes, we solve the Schrödinger equation numerically. The coherent dynamics of the system is governed by

$$i\frac{d}{dt}|\Psi(t)\rangle = H_I|\Psi(t)\rangle, \quad (6)$$

where H_I is given in Eq. (1), and $|\Psi\rangle$ is the state vector described the atom-cavity system. Let us consider an alternative basis of one manifold only producing one polarized photon in cavity 1

$$|A\rangle = |g\rangle \otimes |00\rangle_1 \otimes |11\rangle_2, \quad (7)$$

$$|B\rangle = |e\rangle \otimes |00\rangle_1 \otimes |11\rangle_2, \quad (8)$$

$$|C\rangle = \frac{1}{\sqrt{2}}(|a\rangle|10\rangle_1 + |b\rangle|01\rangle_1) \otimes |11\rangle_2, \quad (9)$$

$$|D\rangle = \frac{1}{\sqrt{2}}|e\rangle \otimes (|10\rangle_1|01\rangle_2 + |01\rangle_1|10\rangle_2), \quad (10)$$

$$|E\rangle = \frac{1}{\sqrt{2}}|g\rangle \otimes (|10\rangle_1|01\rangle_2 + |01\rangle_1|10\rangle_2), \quad (11)$$

$$|F\rangle = \frac{1}{\sqrt{2}}(|a\rangle|10\rangle_1 - |b\rangle|01\rangle_1) \otimes |11\rangle_2, \quad (12)$$

$$|G\rangle = \frac{1}{\sqrt{2}}|e\rangle \otimes (|10\rangle_1|01\rangle_2 - |01\rangle_1|10\rangle_2), \quad (13)$$

$$|H\rangle = \frac{1}{\sqrt{2}}|g\rangle \otimes (|10\rangle_1|01\rangle_2 - |01\rangle_1|10\rangle_2). \quad (14)$$

It is straightforward to check that, under the two-photon resonance condition some of the matrix elements of the Hamiltonian of Eq. (1) are $\langle A|H_I|B\rangle = \Omega(t)$, $\langle B|H_I|C\rangle = \sqrt{2}g_1(t)$, $\langle C|H_I|D\rangle = g_2(t)$, $\langle D|H_I|E\rangle = \Omega(t)$, $\langle H|H_I|G\rangle = \Omega(t)$, $\langle F|H_I|G\rangle = g_2(t)$; while other interaction matrix elements are zero. In the basis $\{|A\rangle, |B\rangle, |C\rangle, |D\rangle, |E\rangle, |F\rangle, |G\rangle, |H\rangle\}$, $|\Psi(t)\rangle$ has the general form

$$|\Psi(t)\rangle = C_a|A\rangle + C_b|B\rangle + C_c|C\rangle + C_d|D\rangle + C_e|E\rangle + C_f|F\rangle + C_g|G\rangle + C_h|H\rangle. \quad (15)$$

Then one can obtain the numerical solution of the system evolution.

The explicit expression for the state vector can be obtained by solving the eigenvalue problem for the Hamiltonian. By diagonalizing the Hamiltonian in the subspace spanned by the above five basis states $|A\rangle, |B\rangle, |C\rangle, |D\rangle$, and $|E\rangle$, one has the dark state

$$|D(t)\rangle = \sin \vartheta |A\rangle - \cos \gamma \cos \vartheta |C\rangle + \sin \gamma \cos \vartheta |E\rangle, \quad (16)$$

where $\tan \gamma = \frac{g_2(t)}{\Omega(t)}$, and $\tan \vartheta = \frac{\tilde{g}_1(t)}{\sqrt{\Omega^2(t) + g_2^2(t)}}$. The two-stage STIRAP proposal can be easily seen from this dark state. One can transfer the system from state $|A\rangle$ to $|E\rangle$ by adiabatically varying the mixing angle ϑ, γ . The steps to generate the polarization-entangled photon pair are: (i) prepare the system in state $|A\rangle$; (ii) change the mixing angle ϑ adiabatically from $\frac{\pi}{2}$ to 0, then the system will evolve into the state $\sin \gamma |E\rangle - \cos \gamma |C\rangle$ (stage 1), (iii) change the mixing angle γ from 0 to $\frac{\pi}{2}$ slowly, the system will end up in the state $|E\rangle$ (stage 2). It is noted that the two cavity modes and the pump field must overlap spatially in order to maintain the adiabatic process. The system adiabatically follows the energy eigenstate (dark state), i.e., the system never involves the intermediate states $|B\rangle$ and $|D\rangle$, so the atomic decay is never involved. The process including the STIRAP is very robust in producing the entangled photons. We have to address that the two-stage STIRAP process can be implemented by sending the atom through the two cavities. In this case, the vacuum Rabi frequencies $g_i(t)$ can be tuned in time for the atom to realize the STIRAP processes.

Figure 2 displays the numerical results of the Schrödinger equation (6). Fig. 2(a) shows the time evolution of the two cavity coupling $g_1(t)$ and $g_2(t)$ as well as the Rabi frequency $\Omega(t)$ of the pump field. Both the cavity modes and pump beam are assumed to have a Gaussian transverse shape, i.e., $\Omega(t) = \Omega_0 \exp[-(\frac{t-\delta t}{\Delta\tau_p})^2]$, $g_1(t) = g_{10} \exp[-(\frac{t}{\Delta\tau_c})^2]$, and $g_2(t) = g_{20} \exp[-(\frac{t-2\delta t}{\Delta\tau_c})^2]$. Here $\Omega_0 = 50\Gamma$, $g_0 = 10\Gamma$, $\Delta\tau_p = 2.5\Gamma^{-1}$, $\Delta\tau_c = 2.5\Gamma^{-1}$, and $\delta t = 4.5\Gamma^{-1}$. Γ^{-1} is a characteristic time, with the value $\Gamma \simeq 2\pi$ MHz for optical CQED and $\Gamma \simeq 2\pi$

KHz for microwave CQED[13]. The above parameters come from the recent cavity QED experiments with high finesse optical resonators[10, 24] or microwave resonators[13]. In optical CQED experiments, the waists of the cavities may be about $w_c \sim 20\mu m$ and the velocity of the atom could be $v \sim 20m/s$, then the width of cavity modes would be about $\Delta\tau_c = w_c/v \sim 1\mu s$ [10, 24]. In microwave CQED experiments, the cavity waist may be $w_c \sim 6mm$, and the velocity of the atom could be $v \sim 0.5km/s$, then the cavity modes width would be about $12\mu s$ [13]. The photon life time of microwave resonators could reach $1ms$ [13]. The necessary condition for adiabatic following can be maintained with these parameters, i.e., $\Omega_0\Delta\tau_p, 2g_0\Delta\tau_c \gg 1$ [25]. In Fig. 2(a), it can be seen that the pump field and the cavity modes have been overlapped partially. The pump field has its center displaced along the atomic beam by an amount of δt relative to the cavity 1 mode. The mode of cavity 2 also has its center displaced the amount of $2\delta t$ relative to the cavity 1 mode. This pulse sequence can maintain the adiabatic process of generating polarization-entangled photon pairs. With the time evolution of the cavity couplings $g_1(t)$, $g_2(t)$ and the pump Rabi frequency $\Omega(t)$, the whole system dynamics is shown in Fig. 2(b). The system starts from state $|A\rangle = |g\rangle \otimes |00\rangle_1 \otimes |11\rangle_2$, via the state $|C\rangle = \frac{1}{\sqrt{2}}(|a\rangle|10\rangle_1 + |b\rangle|01\rangle_1) \otimes |11\rangle_2$, and eventually reaches the state $|E\rangle = \frac{1}{\sqrt{2}}(|10\rangle_1|01\rangle_2 + |01\rangle_1|10\rangle_2) \otimes |g\rangle$. During the process, the states $|B\rangle$, $|D\rangle$, $|F\rangle$, $|G\rangle$, and $|H\rangle$ are never involved. In the end, the atom returns to the ground state, and the photons existing respectively in the two cavities have been entangled. Therefore, the numerical simulations confirm the above STIRAP processes for producing entangled photon pairs.

We now consider the dissipative effect on the coherent interaction of the four-level tripod atom and two cavity modes. This includes the spontaneous decay of atom and damping of cavity modes. As it has been discussed previously, the STIRAP process for generating entangled photon pairs is immune to atomic spontaneous decay. So now only the damping of cavity modes is considered. The evolution of density operator $\rho(t)$ in the presence of the cavity decay is described by the master equation[26]:

$$\frac{\partial\rho}{\partial t} = -i[H_I, \rho] + L_1\rho + L_2\rho, \quad (17)$$

where the cavity dissipative terms are

$$L_1\rho = \kappa \sum_{\xi=+,-} (2a_{1\xi}\rho a_{1\xi}^\dagger - a_{1\xi}^\dagger a_{1\xi}\rho - \rho a_{1\xi}^\dagger a_{1\xi}), \quad (18)$$

$$L_2\rho = \kappa \sum_{\xi=+,-} (2a_{2\xi}\rho a_{2\xi}^\dagger - a_{2\xi}^\dagger a_{2\xi}\rho - \rho a_{2\xi}^\dagger a_{2\xi}), \quad (19)$$

2κ is the one side decay of the two cavities, while the other side of the cavities are assumed to be perfectly reflecting. To solve the master equation numerically, we have used the Monte Carlo wave function (MCWF) formalism from the quantum trajectory methods[27, 28]. The following results are averaged over enough realizations of quantum trajectories.

Figure 3 depicts the numerical results of the master equation (17) in the presence of cavity dissipation. Here the parameters are chosen as in Fig. 2. We consider the evolution of the system toward the entangled states $|E\rangle$ with the different cavity decay rate κ , i.e., $\kappa \simeq 0.01g_0, 0.1g_0$ and g_0 ($g_0 \simeq 10\Gamma$). In Fig. 3(a), the cavity decay rate is $\kappa \simeq 0.01g_0$, which represents the high-Q strong coupling situation. The system starts from the state $|A\rangle$, evolves into the entangled state $|E\rangle$ with a probability $p \simeq 0.80$, i.e., the success probability of generating entangled photon pairs is 80%. The fidelity between the final state and the EPR state $F = |\langle EPR|\Psi(t = +\infty)\rangle|$ is higher than 90%, as shown in Fig. 4. In Fig. 3(b), the cavity decay rate is $\kappa \simeq 0.1g_0$, which corresponds to generally strong coupling situation. The success probability of producing the entangled photon pairs is about 50%. In Fig. 3(c), the cavity decay rate is $\kappa \simeq g_0$, which corresponds to the weak coupling situation. The success probability of producing the entangled photon pairs is neglectable.

To further gauge the performance of the scheme we plot the success probability P and fidelity F as a function of κ/g_0 in Fig. 4. When $\kappa \sim 0.1g_0 - 0.01g_0$, the success probability is about 50%–90%, while the fidelity is very high. The parameters from the recent cavity QED experiments with high finesse optical and microwave resonators are $(g_0, \kappa)/2\pi \simeq (16, 1.4)$ MHz [29], $(g_0, \kappa)/2\pi \simeq (16, 3.8)$ MHz [30], and $(g_0, \kappa)/2\pi \sim (47, 1)$ KHz[13], in line with the regime of the present scheme. It can be seen from Fig. 4 that the cavity decay strongly affects the success probability of generating entangled photon pairs. However, the fidelity of producing the photon pairs has only been weakly affected by cavity decay. To generate entangled photons more efficiently, the transit time for the atom passing through a cavity should be within the characteristic life time of the cavity. Therefore, one has to implement this proposed scheme in the strong coupling domain.

3. Summary

In summary, we have proposed a cavity quantum electrodynamics scheme that can deterministically generate EPR polarization-entangled photon pairs, by means of a four-level tripod

atom successively coupling to two high-Q optical cavities presenting polarization degeneracy. This proposal relies on the cavity-QED system and counterintuitive stimulated Raman adiabatic passage process. It is robust against atomic spontaneous decay and should have potential applications in quantum information processing.

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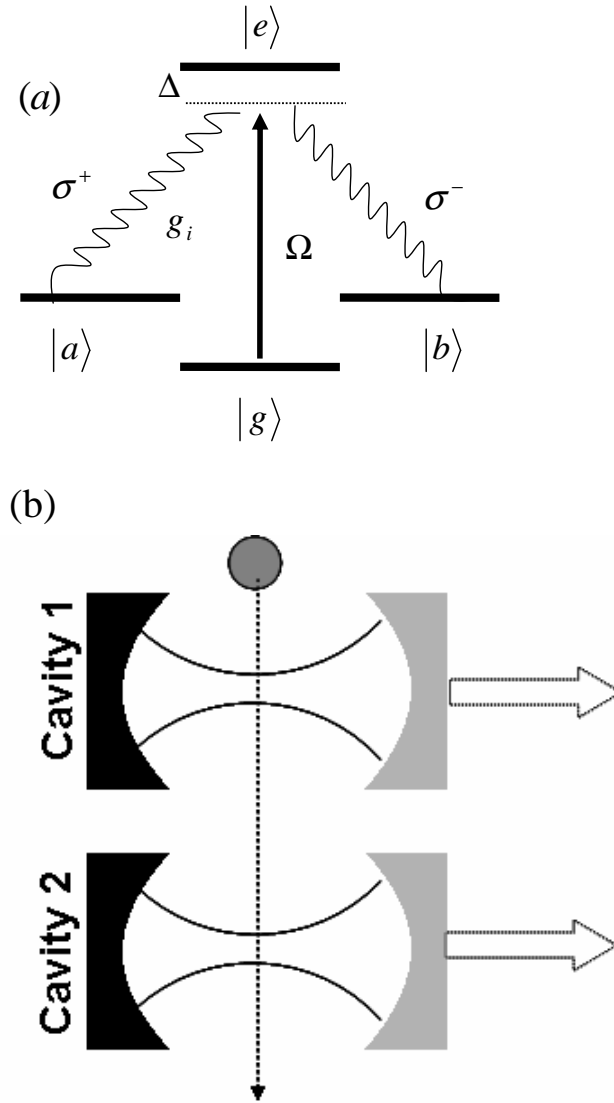


Fig. 1. (a) Tripod four-level atomic system under consideration. (b) Proposed setup for the deterministic production of polarization EPR entangled photon pairs.

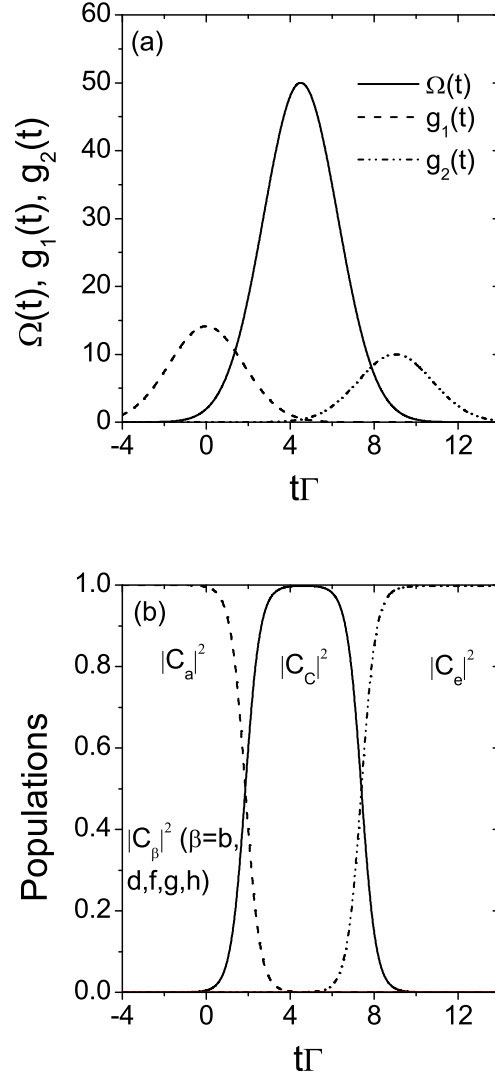


Fig. 2. (a) Time evolution of the coupling $g_1(t), g_2(t)$ and Rabi frequency $\Omega(t)$. The parameters are chosen as, $\Omega_0 = 50\Gamma$, $g_0 = 10\Gamma$, $\Delta\tau_p = 2.5\Gamma^{-1}$, $\Delta\tau_c = 2.5\Gamma^{-1}$, and $\delta t = 4.5\Gamma^{-1}$. (b) Coherent evolution of the cavity-atom system in terms of the basis states expansion coefficients $|C_\alpha(t)|^2$, ($\alpha = a, b, \dots, h$).

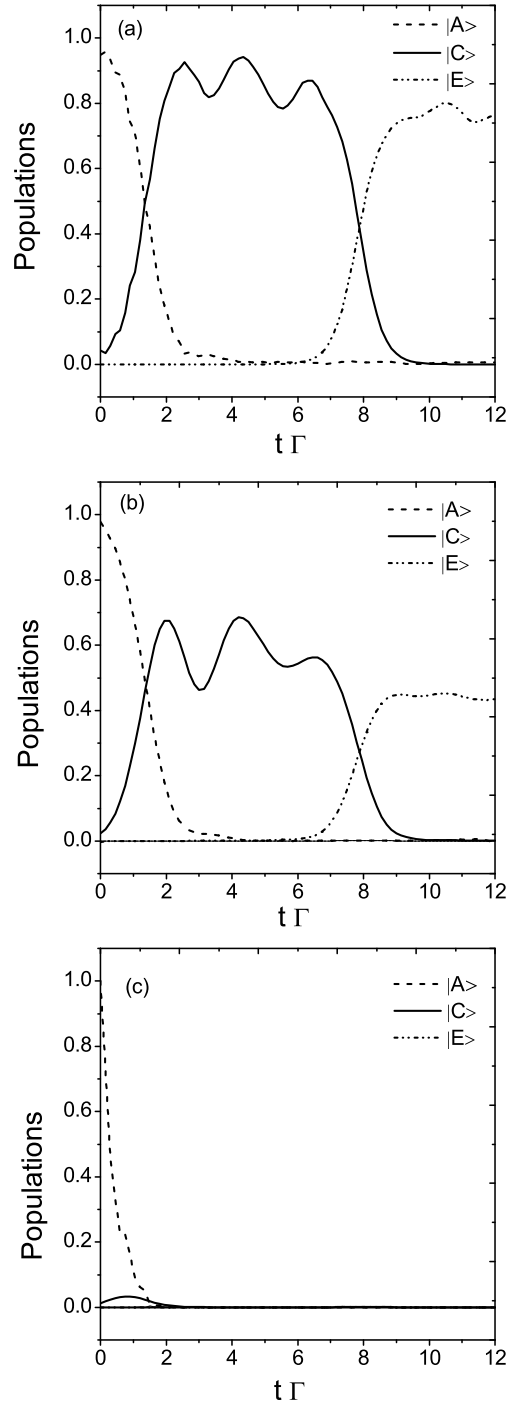


Fig. 3. The evolution of the system in the presence of cavity dissipation. Parameters are chosen as in Fig. 2, but with different cavity decay rates, i.e., $\kappa \sim 0.01g_0$ for 3(a), $0.1g_0$ for 3(b), and g_0 for 3(c).

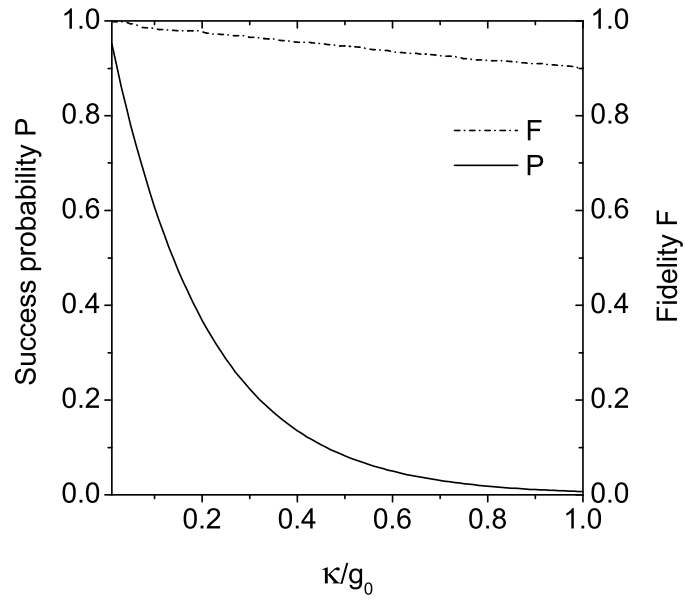


Fig. 4. Plots of the success probability P and fidelity F vs κ/g_0 , other parameters as those in Fig. 2.